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The Interaction of Stability and Fatigue Related Brace Forces in Cross Frame Members of Steel I Girder Bridge Systems

A.D. Battistini[1], S.M. Donahue[2], W.H. Wang[3], T.A Helwig[4], M.D. Engelhardt[5], K.H. Frank[6]

Abstract

The stability of steel bridges is improved by using cross frames, which provide lateral and torsional restraint along the girder length. In order to be considered an effective brace, the cross frame must satisfy both strength and stiffness requirements. It is imperative the stiffness of the cross frame be accurately calculated to ensure the associated cross frame forces and behavior are realistic representations of the brace.

Cross frames can utilize a variety of layouts: the X-Type and K-Type cross frames are commonly used in current practice for steel I-girder bridges, while the single diagonal Z-Type cross frame is being researched at the University of Texas at Austin as part of a TxDOT sponsored research project.

During the design of a steel bridge, the engineer must select a cross frame that provides adequate stiffness to allow for buckling between the brace points while also adhering to maximum fatigue stress limits. If the fatigue stresses are exceeded, the engineer sometimes chooses to use cross frame members with a larger area. The increased stiffness of the members with more area causes the cross frame to attract more forces under fatigue loading, which can lead to exceeding the maximum allowable fatigue stresses. The circular nature of this problem can lead engineers to require larger, heavier cross frames, to use more braces along the girder length, and in some cases, to add an extra girder line.

Previous research at the University of Texas at Austin has shown the stiffness of cross frames with eccentrically connected members, like the angles typically used in X-Type and K-Type cross frames, is significantly less than predicted by analytical equations and truss-type computer models. A case study using a validated finite element model was performed to examine the interaction between brace stiffness and fatigue-induced forces. Recommendations for cross

[1] Clinical Assistant Professor, Washington State University, <a.battistini@wsu.edu>
[2] Graduate Research Assistant, University of Texas at Austin
[3] Structural Engineer, SBM Offshore
[4] Associate Professor, University of Texas at Austin, <thelwig@mail.utexas.edu>
[5] Dewitt C. Greer Centennial Professor in Transportation Engineering, University of Texas at Austin
[6] Chief Engineer, Hirschfeld Industries, Austin, TX

frame stiffness from large-scale experimental testing will be discussed, as well as suggestions for modifying the stiffness in commercial design software.

1. Introduction

Cross frames are critical to the stability of straight and curved steel bridges. The main function of cross frames is to provide lateral stability to the individual girders, thereby increasing the buckling strength of the overall system. The critical stage for cross frames is construction, when the full weight of the concrete deck, as well as additional construction loads, acts on the non-composite steel section. Furthermore, cross frames help to strengthen the completed bridge structure by distributing loads from one girder to adjacent girders. These loads can be the result of lateral wind or earthquake forces, live loads from traffic, or as in the case for curved bridges, the cross frames resist the twist of the superstructure under dead load. In all cases, in order to provide an effective brace, the cross frame must satisfy both strength and stiffness requirements (Winter 1958).

Steel bridge cross frames utilize a variety of layouts, including X-Type and K-Type cross frames comprised of single angle members. The Texas Department of Transportation recommends three possible angle sizes for the braces: L4x4x3/8, L5x5x1/2, and L6x6x9/16 (TxDOT 2006). The current paper will focus on the behavior of the X-Type cross frames, as shown in Figure 1.

Figure 1: (a) X-Type Cross Frame

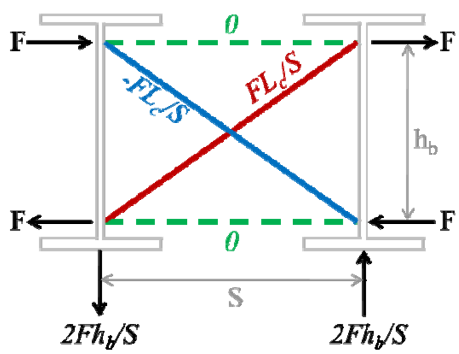
The current version of the AASHTO Specification allows a “rational analysis” to be performed to determine the cross frame spacing, permitting longer distances between braces than the previous requirement of 25ft (AASHTO 2013). While there are potential cost savings from reducing the number of required cross frame lines, it is most important the analysis being performed accurately accounts for the stiffness of the cross frame.

Typically, an increase in the stiffness of a brace will lead to an increase in the forces of the members of that brace. This relationship causes a difficult problem for designers when fatigue-induced forces govern the design of the cross frames. AASHTO currently employs fatigue categories for various details on the superstructure of a steel bridge, including the cross frame members, which are usually welded to gusset plates prior to being either bolted or welded to the cross frame connection plates (2013). The fatigue category limits the stress ranges in the members to a critical value, depending on both finite life and infinite life approximations (AASHTO 2013). If the cross frame member exceeds this critical value, the logical solution is to increase the cross sectional area of the member, thereby reducing the stress range. However, the increased stiffness of the members with more area causes the cross frame to attract more forces under fatigue loading, and upon re-analysis, the forces induced in the member could still exceed the critical stress range. Repeating this process can lead engineers to require larger, heavier cross frames, to use more braces along the girder length, and in the extreme case, to add an extra girder line.

2. Cross Frame Stiffness

Since the increase in member forces primarily results from the increase in brace stiffness, it is very important the analysis program used is accurately capturing the actual stiffness of the cross frame. Research conducted at The University of Texas at Austin has extensively examined the stiffness and fatigue behavior of these brace layouts (Wang 2013, Battistini et al 2013, Wang et al 2012, Battistini et al 2012).

The current model used for determining the torsional brace stiffness of an X-Type cross frame typically uses truss elements for the members, with forces applied as shown in Figure 2. The force couple represents the uniform moment applied to the brace as the adjacent girders begin to buckle. Using a displacement analysis, the rotation of the brace is obtained, and the resulting torsional stiffness calculated (Yura 2001).



$$\beta_b = \frac{A_c E S^2 h_b^{\,2}}{L_c^{\,3}}$$

Figure 2: Torsional Brace Stiffness for X Frame

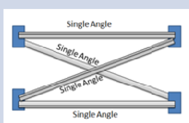
where, F is the applied force, β_b is the torsional brace stiffness, A_c is the cross sectional area of the diagonal member, E is the modulus of elasticity, S is the girder spacing, h_b is the brace height, and L_c is the length of the diagonal.

Although designers may not explicitly use the above formula for torsional brace stiffness, it often is present as an underlying assumption in their analyses. Designers often use a grillage model for the analysis of most bridge geometries. In a grid analysis, the structure is simplified into a two-dimensional plane with all the applied loads acting perpendicular to the plane (Topkaya and Williamson 2003). The members are usually modeled as line elements which are assumed to be axially rigid and have three degrees of freedom at each node, namely transverse displacement, rotation about the member's strong axis, and rotation about the member's longitudinal axis. Bending about the weak axis is typically ignored (Topkaya and Williamson 2003).

In order to create the grid, the cross frames are simplified into an equivalent beam element. The equivalent beam is given a moment of inertia and torsional constant based on different structural analogies of the cross frame system. Some programs may explicitly use the formula given in Figure 2 for the stiffness of the cross frame, while other programs may perform a background line element analysis to obtain the stiffness of the cross frame. In either case, the analysis is most likely overestimating the actual stiffness of the actual cross frame.

Due to the individual eccentricity of the angle members used to comprise the cross frame relative to the cross frame connection plates, the theoretical torsional brace stiffness for typical brace sizes calculated by the equation in Figure 2 or by a line element analysis could be 20-100% more than the actual stiffness (Wang 2013). Table 1 highlights the discrepancies of a specimen that was tested as part of the project.

Table 1: Torsional Cross Frame Stiffness Comparison

Type of Cross Frame		**Test Results [k-in/rad]**	**Solution [k-in/rad]**		**Error [%]**
Single Angle X Frame		872,000	Analytical	1,579,000	82%
			Line Element	1,572,000	81%
			Shell Element	867,000	-1%

Resulting from the project, a reduction factor was proposed to more accurately predict the stiffness of a cross frame. The reduction factor can be applied to the theoretical stiffness to calculate the actual stiffness. The reduction factor is given in Eq. 1 and the actual stiffness in Eq. 2 (Wang 2013).

$$R_{SX} = 1.063 - 0.087\frac{S}{h_b} - 0.159\,\bar{y} - 0.403t \qquad (1)$$

$$\beta_{actual} = R_{SX}\beta_b \qquad (2)$$

where, R_{SX} is the reduction factor for the stiffness of an X-Type cross frame, S is the girder spacing, h_b is the height of the brace, $\bar{y}$ is the distance from the plane of the connection to the centroid of the angle, t is the thickness of the angle, β_{actual} is the actual torsional brace stiffness provided, and β_b is the theoretical brace stiffness calculated by the equation in Figure 2 or from a matching line element model of the system.

If the actual stiffness provided by the cross frames is less than predicted, than it follows the forces in the cross frame members will also be less. Thus, the stress ranges predicted by the theoretical equation, or by a grillage model assuming line element behavior will tend to be higher than the actual stress ranges in the completed structure. By using the actual stiffness provided, designers would be better able to predict the stress range in the cross frames, and might not have an issue satisfying fatigue stress range requirements.

3. Finite Element Model Information

In order to evaluate the effect of modeling the actual cross frame stiffness on the magnitude of cross frame member forces, a model of a curved steel bridge system was created using three-dimensional finite element software. The geometry selected was for a bridge which had presented difficulties during design due to large fatigue-induced forces, and will serve as a case study for examination.

The model constructed followed typical techniques used in previous research to obtain brace forces in plate girder systems [Quadrato 2010, Stith 2010]. The girders were constructed using 8-noded shell elements. Stiffeners were placed at each cross frame location, also made from the 8-noded shell elements. The stiffeners were placed at the exact location and connected to the web elements using constraint equations. In the case of the curved bridge, the girders were modeled along the horizontal curve and contained a dapped end detail. For comparison with a supplied grillage model analysis, the model also contained a concrete deck constructed from shell elements, using elastic properties of the concrete material.

The cross frames were modeled using line elements that framed into the web-flange interface, connecting at the nodes of the stiffeners. The cross frame stiffness was first modeled using the theoretical formulation, and then subsequently modeled with the reduced stiffness prescribed by Eqs. 1 and 2. An isometric view of the curved bridge model is shown in Figure 3.

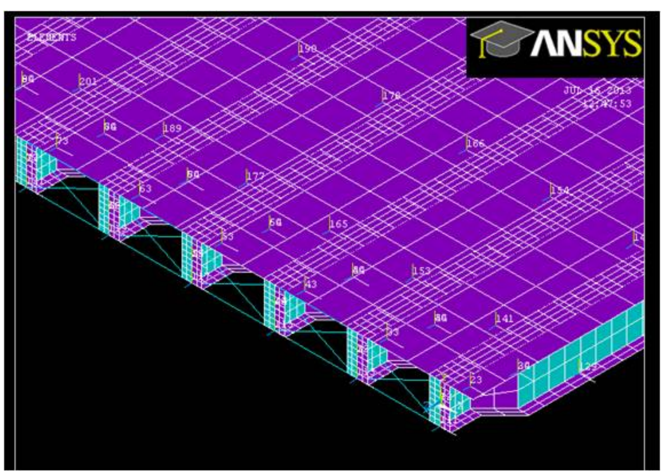


Figure 3: Three-Dimensional Finite Element Model of Curved Girders with Cross Frames

4. Case Study: Single-Span Curved Girder System

The case study to be evaluated will look at the effect proper modeling of cross frame stiffness can have on the force range in the cross frame members. The study will look specifically at two phases during the design process: the “initial design”, in which the grid model indicated AASHTO fatigue limit states were exceeded, and the “final design”, in which the grid model indicated AASHTO fatigue limit states were satisfied. To further validate the three-dimensional finite element model, comparisons will be made with results from the grid model for both the initial and final design phases. Subsequently, the stiffness of the cross frame in the three-dimensional model will be more accurately modeled to include the reduction factor of Eq. 1, and the initial geometry will be further investigated to see the response of member forces.

The initial design contains plans for a single span curved I-girder bridge using 8 girders and the TxDOT XF2 cross frame detail (TxDOT 2006). During design, fatigue issues were indicated by the bridge software package, which consisted of a grillage model. After adjusting the girder cross sectional properties, cross frame spacing, and cross frame member type, the fatigue stress range in the cross frames was still larger than acceptable. The solution resulted in the final design, which includes an additional girder line, adds two extra lines of cross frames, and increases the area of the cross frame members to the TxDOT XF3 detail (TxDOT 2006). The following subsection describes the bridge in full detail.

Bridge Layout and Geometry
The initial design of the bridge consisted of 8 single span curved girders spaced at 8.571 ft. The outermost girder on the curve had a length of 164.991 ft and a radius of curvature of 1943.86 ft. The girder cross section geometry and bracing details are highlighted in Table 2.

Results from the grid analysis indicated the AASHTO Fatigue I limit state controlled the design, and the forces exceeded the allowable limit. Designers attempted to satisfy the limit state by modifying the initial design cross frame member areas, girder spacing, and number of cross frame lines. Finally the designers were forced to add an additional girder line which reduced the girder spacing, and to add additional cross frame lines and larger cross frame member areas to satisfy the design requirements. The layout of the final design is given in Figure 4 and the associated geometry in Table 2.

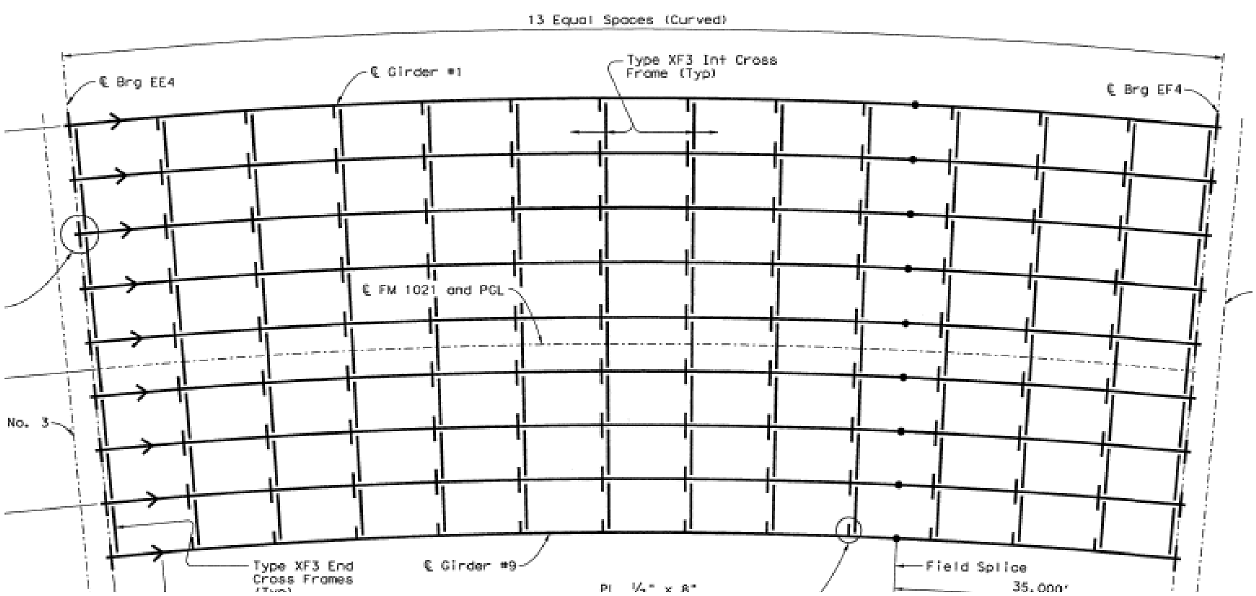


Figure 4: Case Study- Final Design Layout

Table 2: Case Study- Bridge Geometries

Case Study- Bridge Layout and Geometry		
	Initial Design	**Final Design**
Girder Properties		
Number of Girders	8	9
Girder Spacing	8.571 ft	7.5 ft
Deck Overhang	3 ft	3 ft
Radius of Curvature	1883.86-1943.86 ft	1883.86-1943.86 ft
Number of Spans	1	1
Span Length	159.713-164.991 ft	159.713-164.991 ft
Web Depth	68 in	68 in
Web Thickness	0.625 in	0.625 in
Flange Width	24 in	24 in
Top Flange Thickness	1-1.25 in	1.25 in
Bottom Flange Thickness	1-2.25 in	1-2 in
Dapped End Length	85 in (both ends)	85 in (both ends)
Dapped End Depth	42 in (both ends)	42 in (both ends)
Bracing Information		
Cross Frame Arrangement	Radial, Equal Spaces	Radial, Equal Spaces
Total Number of Cross Frames	12	14
Cross Frame Spacing	14.52-15.00 ft	12.28-12.69 ft
Cross Frame Type	TxDOT XF2	TxDOT XF3
Angle Type	L5x5x1/2	L6x6x9/16
Angle Area	4.75 in^2	6.45 in^2
Brace Height	58 in	58 in
Intermediate Stiffeners		
Stiffener Width	8 in	8 in
Stiffener Thickness	0.50 in	0.50 in
Bearing Stiffeners		
Stiffener Width	11 in	11 in
Stiffener Thickness	1.25 in	1 in

When comparing to commercial bridge modeling software, determining the specific technique for placement of loads and their associated magnitudes may not be clear. Therefore, loads were applied in ANSYS consistent with the current AASHTO LRFD Specification (2013) for Fatigue I and Fatigue II limit states. The specification calls for a design lane load of 0.64 klf (kips/linear ft) to be applied over a 10 ft width per lane. The lane load does not include the 1.15 impact factor (AASHTO 2013). Using the grillage software output, the bridge was assumed to contain 4 design lanes of traffic. The lane live load was divided equally amongst the deck nodes on which it acted.

Superimposed on the design lane load is either the design truck or tandem, applied as moving point loads within the design lane. The design truck has a fixed 30 ft spacing between the rear axles as specified for fatigue analyses. The moving point loads are multiplied by the 1.15 impact factor. A schematic is shown in Figure 5 on how the point loads were applied. Corner nodes of the deck shell elements were set on a 3 ft grid. The point loads were then applied at the nearest node for analysis. The truck (or tandem) was run along the outside girder first, and repeated across the width of the bridge.

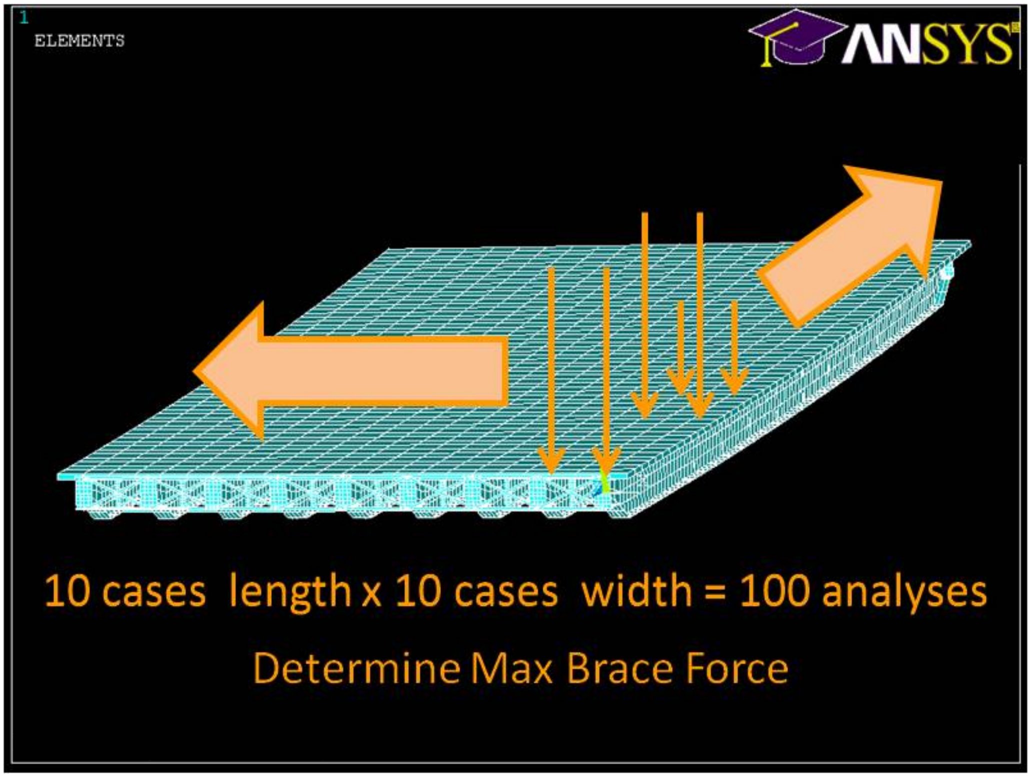


Figure 5: Case Study- Application of Design Truck Loads in ANSYS

In order to compare with the results given to the research team, the area of the line elements were selected to first model the equivalent stiffness calculated by the grillage model. Since the grillage model accounted for the actual height of brace, and the cross frames in the ANSYS model framed into the web-flange interface, slight modifications to the area of the line elements were made.

Initial Design Comparison

Analysis was performed on the initial design geometry to the best extent available from the plans. The fatigue truck and tandem were each run at the 100 different locations outlined in Figure 5, and the maximum force in each cross frame member was identified.

As previously discussed, the initial design was controlled by the Fatigue I limit state. Analysis in ANSYS showed the truck to induce much larger force in the cross frames than the tandem for the given geometry. The location of the maximum forces due to the suite of analysis cases was in the center bay, in the braces near the center. See Figure 6 for more detail.

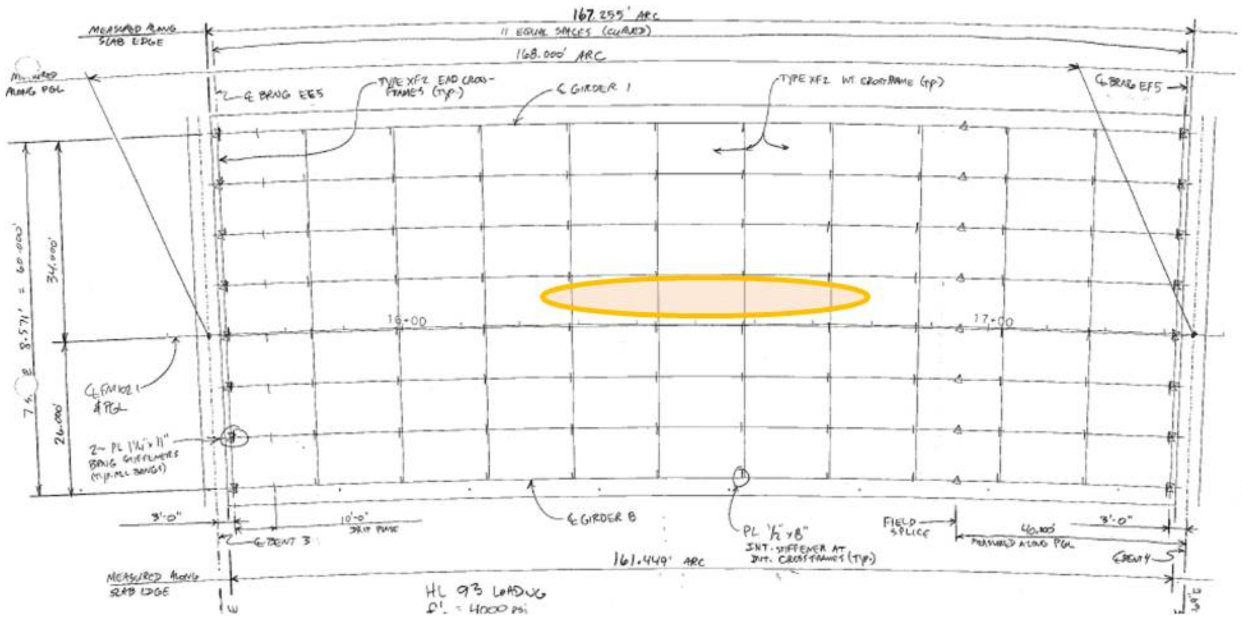


Figure 6: Case Study- Location of Maximum/Minimum Forces in ANSYS and Grillage Model (Initial Design)

When considering fatigue, it is important to consider the range of force a given cross frame member may experience. The range of force is the value provided by the grillage model output and is what the ANSYS forces will be compared against. From the information obtained by the authors, it seems the grillage model software takes the maximum force in each cross frame member due to the series of loads and subtracts the minimum force in each member found for the same series of loads. This approach is very conservative as it assumes that every “cycle” must now consist of the placement of a truck in the precise locations to provide both the maximum and minimum possible forces.

Results from the initial design analysis showed fair agreement between the ANSYS and grillage model output. The results for the center bay are given in Table 3. The brace numbering scheme began at the right end of the bridge as viewed in Figure 6, while the bay numbering scheme began at the bottom.

One important observation from the obtained data is the discrepancy between the force range in the top chords of these braces. Since the ANSYS software includes modeling of the concrete deck as well as the three dimensional location of the cross frames relative to the deck, the force range in the top strut is very low. The grillage model cannot identify this extra restraint, making the force range in the top chord quite high. Additionally, due to the way the cross frames are modeled as equivalent beams in the grillage model, the top and bottom chords undergo the same force range as well as the diagonals. This differs from the ANSYS model predictions.

Despite these differences, the maximum force range still occurs in the bottom strut in both models, the magnitude of which was similar for most locations.

Table 3: Case Study- Results for Cross Frame Member Forces in Center Bay of Initial Design

Initial Design Comparison- Bay 4

Loading Condition: Fatigue I, Design Truck

Maximum Brace Forces (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	1.90	0.00	3.10	3.30
2	1.27	9.67	8.63	6.33
3	1.75	16.49	12.01	9.44
4	2.06	20.05	13.33	10.45
5	2.37	21.29	14.12	10.60
6	2.49	21.91	14.58	10.43
7	2.50	22.22	14.84	10.63
8	2.41	22.27	14.79	11.22
9	2.11	21.97	14.40	11.56
10	1.77	18.55	13.12	10.67
11	1.30	10.84	9.21	7.00
12	1.92	0.96	2.67	3.54

Minimum Brace Forces (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	-0.13	0.00	-5.01	-4.44
2	0.00	-5.43	-3.44	-5.72
3	0.00	-8.40	-3.92	-6.17
4	0.00	-8.93	-3.45	-6.15
5	0.00	-9.72	-2.91	-6.63
6	0.00	-10.20	-2.78	-7.06
7	0.00	-10.60	-2.77	-7.24
8	0.00	-10.62	-2.91	-6.98
9	0.00	-10.48	-3.65	-6.83
10	0.00	-10.03	-4.06	-6.74
11	0.00	-6.91	-3.89	-5.96
12	0.00	-1.31	-4.41	-5.83

Force Range (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	2.04	0.00	8.11	7.75
2	1.27	15.10	12.07	12.05
3	1.75	24.88	15.93	15.61
4	2.06	28.98	16.78	16.60
5	2.37	31.01	17.03	17.23
6	2.49	32.11	17.36	17.49
7	2.50	32.81	17.61	17.86
8	2.41	32.89	17.70	18.20
9	2.11	32.44	18.05	18.38
10	1.77	28.59	17.18	17.40
11	1.30	17.75	13.10	12.96
12	1.92	2.27	7.07	9.37

Force Range (Grillage Model)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	0.25	0.25	3.00	3.00
2	13.47	13.47	4.45	4.45
3	24.27	24.27	6.09	6.09
4	31.50	31.50	5.85	5.85
5	35.92	35.92	6.17	6.17
6	38.69	38.69	6.53	6.53
7	38.69	38.69	6.53	6.53
8	35.92	35.92	6.17	6.17
9	31.50	31.50	5.85	5.85
10	24.27	24.27	6.09	6.09
11	13.47	13.47	4.45	4.45
12	0.25	0.25	3.02	3.02

Final Design Comparison

The next stage in the case study was to compare the force ranges from the ANSYS model to the grillage model for the final geometry. The comparison was done for the Fatigue II limit state, which was indicated by the output of the grillage model software to be the controlling scenario. The location of the maximum force range was again identified at the braces towards the very center of the bridge, as indicated in Figure 7.

As discussed for the initial design, the force ranges in the braces were compared and found to be in relative agreement for the maximum values. For this loading condition ANSYS indicated the force range to be slightly higher. A sample of the data is shown in Table 4.

The previous discrepancies in the force ranges in the top chords and diagonals are again observed in the data. The maximum force range was identified in the bottom strut of the braces and showed fair agreement between the two models, especially considering the number of unknown characteristics about the internal calculations of the grillage software.

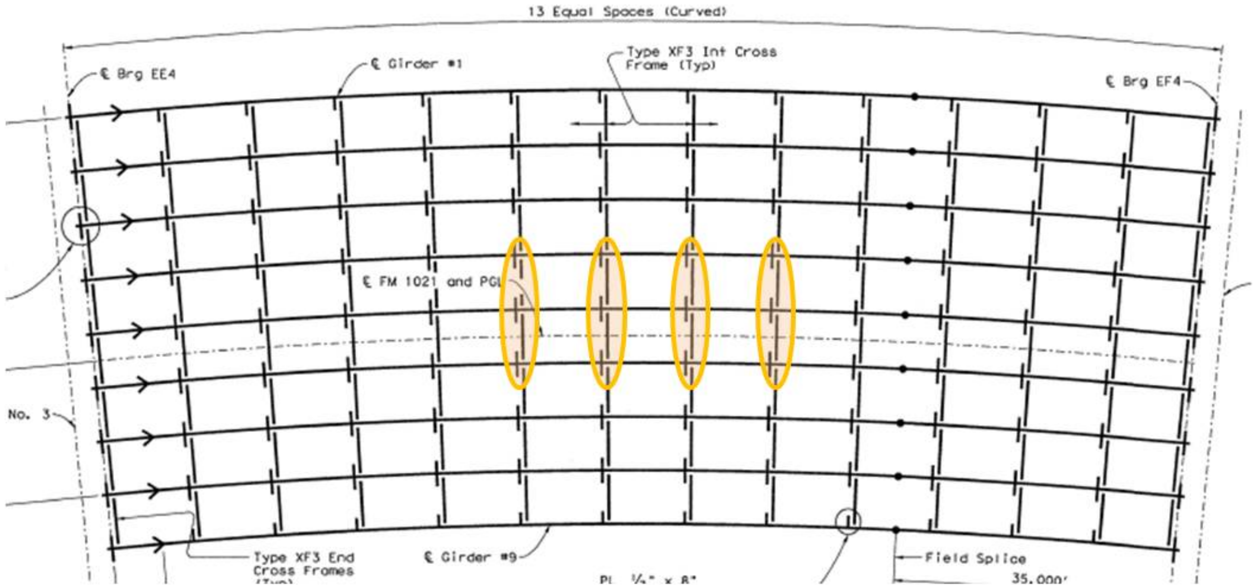


Figure 7: Case Study- Location of Maximum/Minimum Forces in ANSYS and Grillage Model (Final Design)

Table 4: Case Study- Results for Cross Frame Member Forces in Center Bay of Final Design

Final Design Comparison- Bay 5

Loading Condition: Fatigue II, Design Truck

Maximum Brace Forces (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	0.86	0.00	1.33	1.29
2	0.72	4.86	3.88	3.22
3	1.00	7.22	4.91	4.12
4	1.27	8.27	5.25	4.44
5	1.50	9.32	5.47	4.80
6	1.68	9.82	5.59	4.84
7	1.78	10.00	5.62	4.78
8	1.79	10.02	5.73	4.86
9	1.71	9.92	5.79	4.95
10	1.56	9.60	5.77	5.00
11	1.34	9.13	5.73	5.02
12	1.06	8.19	5.41	4.72
13	0.70	5.34	4.15	3.57
14	0.93	0.71	0.49	1.94

Minimum Brace Forces (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	-0.19	0.00	-3.02	-2.99
2	0.00	-2.71	-2.06	-2.48
3	0.00	-4.57	-1.89	-2.94
4	0.00	-5.30	-1.45	-3.25
5	0.00	-5.41	-1.42	-3.28
6	0.00	-5.42	-1.34	-3.36
7	0.00	-5.39	-1.24	-3.39
8	0.00	-5.58	-1.23	-3.46
9	0.00	-5.74	-1.32	-3.49
10	0.00	-5.92	-1.43	-3.51
11	0.00	-5.81	-1.58	-3.53
12	0.00	-5.34	-2.03	-3.35
13	0.00	-3.19	-2.14	-2.55
14	-0.02	-0.74	-3.04	-2.96

Force Range (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	1.05	0.00	4.35	4.28
2	0.72	7.57	5.94	5.70
3	1.00	11.79	6.80	7.06
4	1.27	13.57	6.70	7.69
5	1.50	14.73	6.89	8.07
6	1.68	15.24	6.92	8.20
7	1.78	15.39	6.86	8.17
8	1.79	15.60	6.96	8.32
9	1.71	15.66	7.11	8.44
10	1.56	15.52	7.20	8.51
11	1.34	14.94	7.31	8.55
12	1.06	13.52	7.44	8.07
13	0.70	8.53	6.29	6.13
14	0.95	1.44	3.54	4.90

Force Range (Grillage Model)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	0.01	0.01	0.08	0.08
2	6.39	6.39	0.59	0.59
3	9.28	9.28	1.15	1.15
4	11.56	11.56	1.00	1.00
5	13.25	13.25	1.44	1.44
6	13.73	13.73	0.67	0.67
7	13.99	13.99	0.63	0.63
8	13.99	13.99	0.63	0.63
9	13.73	13.73	0.67	0.67
10	13.22	13.22	1.44	1.44
11	11.48	11.48	0.99	0.99
12	5.95	5.95	2.98	2.98
13	3.98	3.98	2.26	2.26
14	0.00	0.00	0.06	0.06

Effect of Stiffness Reduction of Cross Frame on Force Range

The final stage of the case study was to examine the effect of properly modeling the cross frame stiffness of the system. As previously discussed, the use of single angle members leads to significant reductions in cross frame stiffness due to the eccentricity of the member. The use of a reduction factor, R_{SX}, as outlined in Eqs. 1 and 2 was employed to examine the effect on the initial design geometry. The results of the series of analyses are given in Table 5.

Table 5: Case Study- Results for Cross Frame Member Forces in Center Bay of Initial Design Including the Reduction Factor

Initial Design Comparison- Bay 4

Loading Condition: Fatigue I, Design Truck

Force Range (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	2.04	0.00	8.11	7.75
2	1.27	15.10	12.07	12.05
3	1.75	24.88	15.93	15.61
4	2.06	28.98	16.78	16.60
5	2.37	31.01	17.03	17.23
6	2.49	32.11	17.36	17.49
7	2.50	32.81	17.61	17.86
8	2.41	32.89	17.70	18.20
9	2.11	32.44	18.05	18.38
10	1.77	28.59	17.18	17.40
11	1.30	17.75	13.10	12.96
12	1.92	2.27	7.07	9.37

Force Range with R Factor (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	1.32	0.00	7.01	6.85
2	0.41	8.70	7.54	7.47
3	0.65	15.80	10.94	10.78
4	0.82	20.12	12.55	12.37
5	0.93	22.39	13.27	13.23
6	0.97	23.89	13.76	13.77
7	0.97	24.56	13.97	14.07
8	0.93	24.13	13.93	14.16
9	0.81	22.49	13.68	13.80
10	0.66	18.29	12.21	12.11
11	0.43	10.80	8.29	8.11
12	0.96	0.82	6.43	7.24

Referencing the above results, one can see the force range is reduced significantly when the R_{SX} factor is accounted for in the analysis. For reference purposes, the R_{SX} factor for the given cross frame geometry was nearly 0.50.

For the cross frame members with the largest force ranges, inclusion of the reduction factor results in a 25% decrease in the cross frame force range. In terms of design, this reduced force can help alleviate fatigue design problems. The following table examines the ratio between the force range with the R_{SX} factor included to the original ANSYS predicted force range.

Table 6: Case Study- Ratio of Cross Frame Member Forces in Center Bay of Initial Design Including the R_{SX} Factor to the Original Calculation

Ratio of Force Range With/Without R Factor (ANSYS)				
Brace	Top Chord [k]	Bottom Chord [k]	Diagonal 1 [k]	Diagonal 2 [k]
1	0.65	-	0.86	0.88
2	0.32	0.58	0.62	0.62
3	0.37	0.63	0.69	0.69
4	0.40	0.69	0.75	0.74
5	0.39	0.72	0.78	0.77
6	0.39	0.74	0.79	0.79
7	0.39	0.75	0.79	0.79
8	0.39	0.73	0.79	0.78
9	0.38	0.69	0.76	0.75
10	0.37	0.64	0.71	0.70
11	0.33	0.61	0.63	0.63
12	0.50	0.36	0.91	0.77

Referencing Table 6 it is clear the proper modeling of the stiffness of the cross frame not only effects stability calculations, but also serves an important role in the determination of cross frame fatigue force ranges. Reductions of 20-30% were typical in the most heavily loaded braces, while other braces can see upwards of 60-70% reductions.

Application of Reduction Factor to General Computer Software

In the analysis considered, the R_{SX} factor was applied to the member cross sectional area and the resulting forces were obtained from the ANSYS finite element software. Although this is one viable solution, an alternative would be to apply the reduction factor to the modulus of elasticity, that way stress calculations performed by the program would remain accurate. In addition, the change in elasticity may be an easier way to apply the reduction factor to all the cross frames. Since the stiffness of the members is proportional to AE/L, both methods are acceptable.

5. Conclusions

The following conclusions summarize the information obtained in performing this case study:

- The method in which grillage analysis software determine cross frame "beams" with an equivalent moment of inertia may not result in accurate stiffness and fatigue behavior of the cross frame.
- Increasing the stiffness of a cross frame in a bridge model will increase the amount of force the members of the brace experience.
- To more accurately predict the forces in the cross frames, the reduction factor R_{SX} can be applied to the cross sectional area or modulus of elasticity of the line element cross frame members.
- Including the reduction factor can lead to 20-30% decreases in the fatigue force range for the most heavily loaded members.

The importance of using the R factor to better estimate the cross frame force ranges is highlighted by the initial and final design considered in this case study. Due to fatigue forces calculated by the analysis program, designers were forced to use 35% larger cross frame members, two additional intermediate cross frame lines, and one extra girder line. These additions significantly increased the cost of the project and may not have been necessary due to the overestimation of cross frame force ranges.

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